2009

# Causes and Impacts of Salinization in the Lower Pecos River

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*Great Plains Research* 19 (Spring 2009):27-44


# CAUSES AND IMPACTS OF SALINIZATION IN THE LOWER PECOS RIVER

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**ABSTRACT**—River salinization is a byproduct of water resource development that results from cumulative impacts of flow-regime modifications and crop irrigation. However, historical salinization in the Lower Pecos River is often attributed to natural, high-salinity groundwater. Here, evidence from literature and U.S. Geological Survey gaging stations is reviewed to summarize historical changes associated with water development that potentially contributed to Pecos River salinization. A suite of hydrological changes, initiated in the 1880s, likely contributed to streamflow salinization: (1) reduced flood frequency and magnitude, (2) diminished streamflow, (3) increased evapotranspiration, and (4) increased prevalence of natural, high-salinity groundwater. Salinization is presently highest where these cumulative impacts were greatest (Red Bluff Dam to Girvin, Texas). Prior to water-resource development, higher, fresher streamflows and periodic floods diluted natural, high-salinity groundwater inflows and continuously exported salts from the drainage. Predevelopment salinity was low enough to support at least 44 native fishes, 13 of which have disappeared from the region. Only seven euryhaline natives remain in the most salinized river reach. However, flow-regime restoration and improved irrigation practice could potentially reduce salinization and partially restore a freshwater fauna.

**Key Words:** brine aquifer, cumulative impacts, euryhaline fishes, irrigation, native fishes, natural flow regime, salt balance

## INTRODUCTION

Salinization (salt buildup in soils and waters) is a liability associated with irrigated agriculture (Pillsbury 1981; Williams 1987; Smedema and Shiati 2002) that threatens agricultural sustainability (Jacobsen and Adams 1958; Postel 1989; Ghassemi et al. 1995). Ancient Egypt is the best-known example of an irrigation system in long use (centuries) that avoided salinization (Nace 1972; Pillsbury 1981; Kishk 1986). Salts did not accumulate within irrigated fields or residual waters of ancient Egypt because annual flooding of the Nile River diluted and exported the salts that were produced naturally and via irrigation. In other words, the natural flow regime of the Nile River maintained a salt balance—an equilibrium between salt production and salt export—within the drainage.

Salt balance is characteristic of pristine rivers with natural flow regimes (Holmes 1971; Pillsbury 1981). That is, although the level of salinity is variable among streams worldwide, it is characteristically within the range that is suitable for freshwater organisms (Hynes 1970). Freshwater inflows can even maintain freshwater faunas in terminal lakes of endorheic basins if annual inflows equal or exceed annual evaporation (e.g., Williams and Aladin 1991; Bortnik 1999). However, the natural salt balance of a given stream can be disrupted by hydrological alterations associated with water resource development (e.g., flood control, streamflow storage, streamflow diversion onto croplands) that either reduce salt export or increase evapotranspiration, both of which promote salt accumulation (Holmes 1971; Pillsbury 1981). Accumulating salts eventually contaminate irrigated soils and irrigation-return flows (Elgabaly 1977; Pillsbury 1981; Khan 1982). Saline irrigation-return flows, in turn, contaminate groundwater (Pillsbury 1981; Alyamani 1999; Foster and Chilton 2003) and receiving waterways (Butler and von Guerard 1996; Dennehy et al. 1998; Shirinian-Orlando and Uchrin 2000; Smedema and Shiati 2002). If natural streamflows are severely depleted, saline irrigation-return flows become the dominant source of instream flow

Manuscript received for review, June 2008; accepted for publication, November 2008.

(Howard 1942b; Colby et al. 1956; Dennehy et al. 1998), which can create a brackish or saline environment that is unsuitable for freshwater organisms (Williams 1987; Meybeck et al. 1989; Ghassemi et al. 1995).

Reviews of aquatic conservation concerns in the North American Great Plains make little mention of salinization (Matthews and Zimmerman 1990; Fausch and Bestgen 1997; Dodds et al. 2004; Hubert and Gordon 2007), and when mentioned, it is not linked with irrigated agriculture (Covich et al. 1997). Nonetheless, irrigation throughout the Great Plains has elevated streamflow salinities (e.g., Haney and Bendixen 1953; Dennehy et al. 1998; Zelt et al. 1999). One factor that contributes to this oversight may be that some aquifers of the Great Plains include naturally saline waters (e.g., Feth 1971; Rawson 1982). Presence of natural salinity may overshadow human-caused salinization if there is a perception that aquatic habitats were naturally saline. However, in watersheds highly modified by human disturbances, the relative contributions of naturally saline springs versus human disturbances to river salinization can be uncertain. Further, contemporary studies of river salinization typically focus on proximate factors that contribute to present-day salinity, often concluding, appropriately, that saline springs are a major source of modern-day salts (Havens and Wilkins 1979; Gillespie and Hargadine 1986; Shirinian-Orlando and Uchrin 2000; Hogan et al. 2007). However, from the standpoint of biological conservation, the ultimate (i.e., historical) cause of river salinization is relevant, particularly with respect to historical declines of native biota. Thus, a historical perspective on human-caused hydrological changes is useful to understand the relative contributions of natural and human-related salt production to historical river salinization.

The Lower Pecos River lies at the southwestern edge of the Great Plains in New Mexico and Texas. Certain stretches of this river are saline and harbor a unique aquatic fauna dominated by salt-tolerant taxa (Davis 1980a; Linam and Kleinsasser 1996). However, the predevelopment fauna included many freshwater taxa that have disappeared from salinized river reaches (Davis 1987; Hoagstrom 2003). This suggests salinization was recent, perhaps associated with water resource development. Indeed, high salinity in the Lower Pecos River has been attributed to increased evapotranspiration associated with irrigated agriculture (Gibbs 1970, 1971; Pillsbury 1981; El-Ashry et al. 1985). However, salinization of the Lower Pecos River is also commonly attributed to a brine aquifer near Malaga, New Mexico (Lingle and Linford 1961; Feth 1971; Havens and Wilkins 1979). The goal of this paper is to explore this difference of opinion via a review of historical information with emphasis on alterations of the natural flow regime (Poff et al. 1997). This perspective is significant because, if salinization were facilitated by human alterations of the natural flow regime, then mitigation or reversal of such alterations could potentially reduce salinity and partially restore salinized river reaches.

## THE LOWER PECOS RIVER

The Pecos River is a major tributary to the Rio Grande (Fig. 1) that lies within the Great Plains Physiographic Province (Thornbury 1965; Trimble 1990; Holliday et al. 2002). The Lower Pecos River traverses roughly the downstream half of the drainage (Fig. 1) and consists of two major geomorphic divisions: (1) the Permian Basin upstream and (2) the Edwards Plateau downstream (Thomas 1972). The Pecos River valley and major tributary valleys are relatively wide in the Permian Basin, whereas they are incised within deep canyons in the Edwards Plateau.

Saline strata underlie much of the Pecos River watershed and in some cases are associated with brine aquifers (USNRPB 1942). Local upwellings of brine create saline springs that account for the commonness of place names such as Alkali Spring, Bitter Creek, and Salt Creek throughout the region (Brune 2002). These springs, streams, and seeps contribute salts to the Pecos River, giving its waters a salty taste that was noted by pioneers (Lingle and Linford 1961; Dearen 1996). Thus, even prior to development, the Pecos River was regarded as salty. However, salinity of roughly 0.3‰ is considered undesirable for human consumption and, in this context, salinities above 3.0‰ are considered highly saline (Williams 1987). Thus, the fact that early explorers, pioneers, and their livestock routinely drank from the Pecos River (e.g., Pope 1854; Dearen 1996) indicates a freshwater, rather than saline, aquatic environment. That is, presence of some salts or even periodic or localized brackish conditions does not preclude dominance by freshwater biota, so long as salinity remains relatively low (i.e., <14‰; Hynes 1970; Williams 1996). For example, salinized irrigation return flows in the Black River, a Pecos River tributary near Malaga, New Mexico (Fig. 1) more than double salinity at times (average of 7,750 μS/cm specific conductance in 1977-78), but do not preclude the presence of a relatively diverse fish assemblage that includes native freshwater fishes (Cowley and Sublette 1987). Thus, although water from the predevelopment Pecos River had a

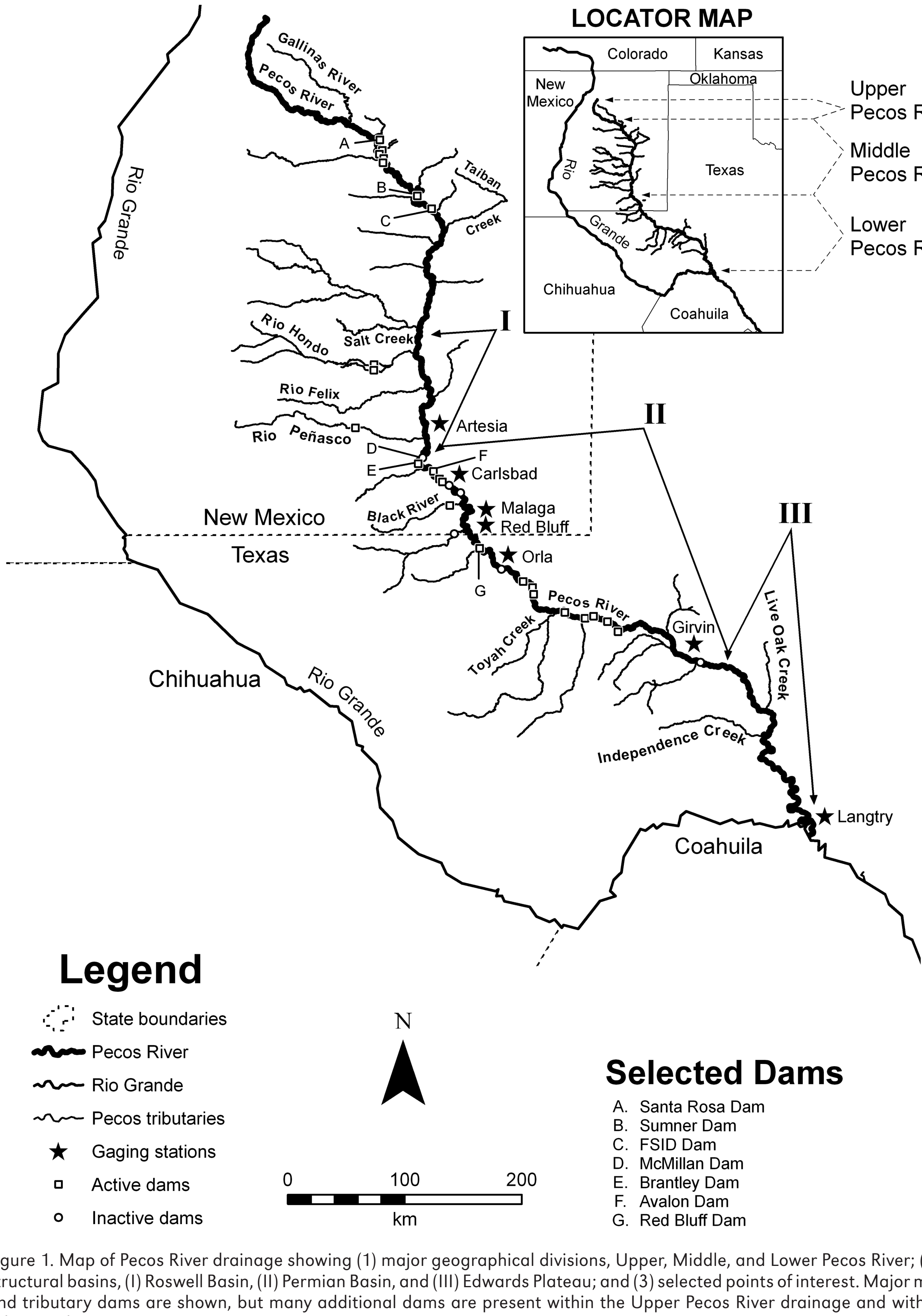


Figure 1. Map of Pecos River drainage showing (1) major geographical divisions, Upper, Middle, and Lower Pecos River; (2) major structural basins, (I) Roswell Basin, (II) Permian Basin, and (III) Edwards Plateau; and (3) selected points of interest. Major mainstem and tributary dams are shown, but many additional dams are present within the Upper Pecos River drainage and within major tributary drainages.

salty taste, it was not necessarily too saline for freshwater organisms.

Prior to development, the Lower Pecos River was navigable upstream from the Rio Grande confluence at least to the New Mexico-Texas state line (Pope 1854). During the exploration and settlement period (roughly 1535 to 1880), it was notoriously difficult to cross due to a swift current, high depth, and shifting-sand substrate (Leftwich 1957; Dearen 1996). At this time, streamflows were a combination of inflows from upstream, local groundwater inflows, and local surface runoff (USNRPB 1942). Some groundwater inflows originated west of the surface-drainage boundary (Sharp 2001; Sharp et al. 2003), extending the groundwater-drainage southwest across a large, albeit arid, region.

Initial water resource development in the Pecos River drainage focused primarily on surface water storage and diversion, but groundwater use increased substantially after 1900 in the Roswell Basin, New Mexico, and after 1948 in the Permian Basin, New Mexico and Texas (USNRPB 1942; Thomas 1959; Lingle and Linford 1961; Ashworth 1990). Five major dams with reservoirs (Avalon, McMillan, Sumner, Red Bluff, Santa Rosa) were constructed for irrigation storage and flood control during the period from 1890 to 1980, one of which (McMillan Dam), was breached and replaced by an additional dam and reservoir in 1988 (Brantley Dam; Hufstetler and Johnson 1993; Fig. 1). Many smaller dams were also constructed throughout the Pecos River drainage (Fig. 1). Throughout the Permian Basin, Pecos River waters were diverted, applied to crops, returned to the Pecos River in concentrated form, and then diverted again (USNRPB 1942). Repeated diversions of surface water, groundwater overdraft, and flood control reduced the Lower Pecos River to a tranquil, sluggish stream that was no longer navigable or even difficult to cross (Dearen 1996). In some locations, streamflow ceased altogether during dry periods (Grozier et al. 1966).

Irrigated agriculture within the Pecos River drainage is generally concentrated within alluvial valleys and alluvium-filled structural basins. The largest agricultural areas are (1) the Fort Sumner Valley (downstream from FSID Dam), (2) the Roswell Basin, (3) the Carlsbad Valley between Carlsbad and Malaga, NM, and (4) the Toyah Basin between Orla and Girvin, TX (USNRPB 1942; Lingle and Linford 1961; Ashworth 1990; Fig. 1). These areas are characterized by alluvial strata that are suitable for farming and overlie substantial aquifers that have been used to supplement surface-water supplies (USNRPB 1942; Lingle and Linford 1961). Irrigated agriculture is rare in the Edwards Plateau portion of the Lower Pecos River because suitable farmland is scarce (USNRPB 1942). Groundwater is less severely exploited in this region, so discharge to the Lower Pecos River remains relatively substantial (Rhodes and Hubbs 1992; Linam and Kleinsasser 1996).

## METHODS

This paper is a synthesis of information on historical alterations of hydrology in the Pecos River drainage associated with water resource development. Main sources of information were (1) the literature and (2) data from U.S. Geological Survey surface-water gaging stations. Gage data were accessed via the Internet (http://waterdata.usgs.gov) and summarized for up to seven gaging stations distributed throughout the study area, depending on the parameter of interest and data availability. Gaging stations with the longest continuous period of record were selected for analysis. The Near Artesia, NM, gaging station (number 08396500) represented inflows to the Lower Pecos River and was also used to represent the predevelopment flow regime because it was established prior to major dam construction upstream. However, no gaging station on the Pecos River predates all human-related hydrological disturbances (USNRPB 1942). The gaging stations of Near Artesia, NM; Near Malaga, NM (number 08406500); Near Orla, TX (number 08412500); and Near Girvin, TX (number 08446500) were used to summarize historical changes in the frequency and magnitude of peak streamflows (defined here as flow events $>30\ m^3/s$). Data from these gaging stations were adequate to illustrate temporal and spatial variation in frequency and magnitude of peak flows. These gaging stations, along with those at Below Dark Canyon in Carlsbad, NM (number 08405200); Red Bluff, NM (number 8407500); and Near Langtry, TX (number 08447410), were used to summarize available data on specific conductance (a measure of salinity) for the period of record (1959 to 2007). Data for the period 1986 through 2005 (the only period with data available for all gages) were used from six gaging stations (Near Artesia, NM; Below Dark Canyon in Carlsbad, NM; Near Malaga, NM; At Red Bluff, NM; Near Orla, TX; and Near Girvin, TX) to characterize contemporary patterns of average streamflow.

Historical information on Pecos River hydrology was interpreted within the context of the Natural Flow Regime paradigm (Poff et al. 1997), which recognizes five major attributes of a flow regime: (1) magnitude of a given flow event, (2) frequency of a given flow event, (3) duration of a given flow event, (4) timing of a given flow event, and (5) rate of change among flow events. Changes to a natural flow regime that may facilitate salt accumulation include reductions in the magnitude and frequency of floods and reductions in streamflow magnitude (Holmes 1971; Pillsbury 1981). Increased evapotranspiration associated with crop irrigation (Gibbs 1970, 1971; Pillsbury 1981) and natural inflows from saline aquifers (Feth 1971; Havens and Wilkins 1979) also may contribute to salinization. Thus, historical information on these effects was also reviewed. Simultaneous consideration of historical flow-regime changes and evapotranspiration changes relative to brine aquifer discharge was intended to provide a comprehensive, albeit qualitative, assessment of factors facilitating historical salinization in the Lower Pecos River.

Literature reporting historical changes in the aquatic fauna of the Lower Pecos River was also reviewed, with an emphasis on fishes (because they were the most studied). The pattern of biological change was presumed to result from abiotic changes within the Pecos River drainage. With regard to salinization, declines of freshwater fishes (fishes that cannot tolerate seawater; Gunter 1942; Smith and Miller 1986; Echelle et al. 1972; Hoagstrom and Brooks 1999) were of particular interest. The historical and recent status of native fishes was summarized for the following three reaches of the Lower Pecos River that differed in the degree of salinization (Rhodes and Hubbs 1992; Linam and Kleinsasser 1996; Hoagstrom 2003): (1) from Brantley Dam to Red Bluff Dam (intermediate salinity), (2) from Red Bluff Dam to Girvin, TX (highest salinity), and (3) from Girvin, TX, to the Rio Grande confluence (lowest salinity).

## RESULTS AND DISCUSSION

### Reduced Flood Frequency and Magnitude

The Lower Pecos River was historically prone to frequent and sometimes severe floods (USNRPB 1942; USPWRPC 1950; Hufstetler and Johnson 1993). Major floods could occur (1) in spring, via snowmelt or rains; (2) in summer, via monsoons; or (3) in fall, via hurricane-related rains (USNRPB 1942). As a result, annual flood peak magnitude, timing, and duration varied among years (e.g., Fig. 2). Historical accounts indicate that floods were frequent prior to water resource development (Leftwich 1957; Dearen 1996).

Frequent floods in the predevelopment Lower Pecos River would have diluted streamflows and facilitated salt

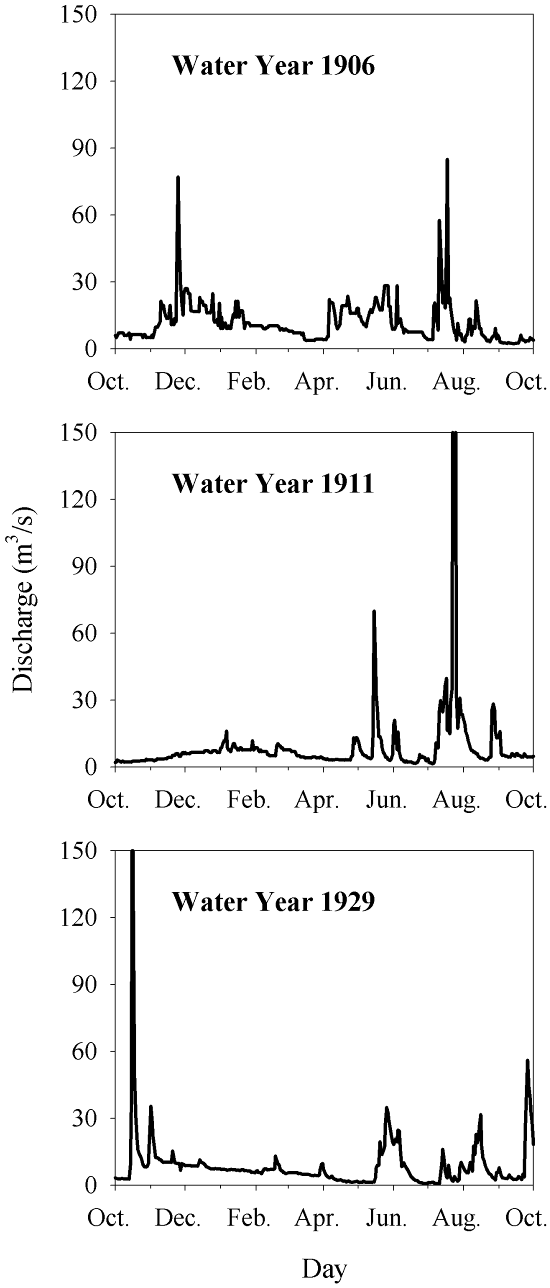


Figure 2. Annual flow regime of the Pecos River near Artesia (U.S. Geological Survey Surface-Water Gaging Station 08396500) by water year (October through September) is shown for selected years to illustrate the variable timing of natural flood peaks caused by snowmelt runoff (March through June), monsoon rains (July through September), and hurricane moisture from the Gulf of Mexico (October). Records shown represent the Pecos River flow regime with minimal upstream flood control (pre-1937). Depletions of streamflows upstream of Artesia in the selected years were largely surface-water diversions, which presumably did not dramatically alter flood periodicity. The Near Artesia, NM, gage represents inflow to Brantley Reservoir, which is the upstream boundary of the Lower Pecos River. Continuous pre-flood-control gage data are unavailable for the Lower Pecos River because of establishment of major reservoirs near Carlsbad, NM, by 1911.

export from the area. Indeed, saline springs and high evaporation rates presently elevate streamflow and reservoir salinity during low-flow periods, but periodic floods dilute them (USNRPB 1942; Grozier et al. 1968). For example, as a result of floods in 1941, the average annual concentration of dissolved solids flowing into Red Bluff Reservoir was roughly half (2,009 mg/l) that in the three previous years (Howard 1942a). Further, the concentration of dissolved solids flowing out of Red Bluff Reservoir was roughly half (1,068 mg/l) the concentration present in the previous water year (Howard 1942a). This dilution effect is an important component of contemporary water management. For example, irrigation storage releases from Sumner Dam, New Mexico (Fig. 1) are often implemented, in part, to reduce salinity in Brantley Reservoir, downstream (Robertson 1997).

Today, floods in the Pecos River drainage rarely exceed reservoir capacities (Longworth and Carron 2003). However, floods originating in the mountainous headwaters formerly reached the Lower Pecos River (USNRPB 1942; Hufstetler and Johnson 1993) but are now captured by Sumner Dam (completed in 1937) and Santa Rosa Dam (completed in 1980; Welsh 1985). Thus, uncontrolled flooding in the vicinity of Red Bluff Reservoir (for example) only occurs when local precipitation is heavy (USNRPB 1942). Floods no longer occur every year in this vicinity and are increasingly rare (Fig. 3). Presumably, river reaches with the lowest flood frequency and magnitude are most susceptible to salt buildup because dilution and export of salts are reduced. Indeed, both the frequency and magnitude of floods has been particularly low between Red Bluff Dam and Girvin, TX, since 1942 (Fig. 3), where streamflow is particularly saline (Fig. 4).

## Diminished Streamflow

Catchment geography and groundwater studies indicate inflows to the Lower Pecos River were substantial. The catchment upstream is 29,474 km$^2$ in extent and includes mountain peaks reaching nearly 4,000 m in elevation, both in the headwaters and in major tributaries that flow from mountains to the west (e.g., the Rio Hondo; USNRPB 1942). This alone suggests inflows would have been substantial and that alpine spring snowmelt was an important component of the natural flow regime. Groundwater inflows were also prominent because of the abundance of karst in the region (USNRPB 1942). Prior to human exploitation (circa 1900), the Pecos River downstream from the Gallinas River confluence received groundwater inflows throughout its length except for a

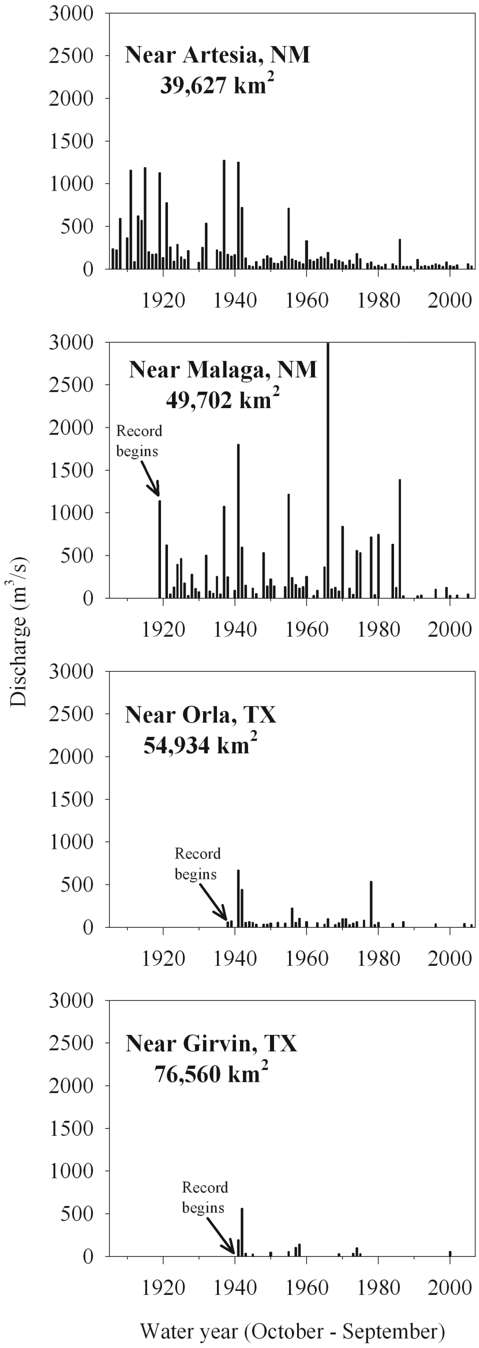


Figure 3. Peak annual streamflows that exceed 30 m$^3$/s by water year (October through September) for the period of record at four U.S. Geological Survey Surface-Water Gaging Stations, presented in upstream to downstream order. The Near Artesia, NM, gage (08396500) represents inflow to Brantley Reservoir, which is the upstream boundary of the Lower Pecos River. The Near Malaga, NM, gage (08406500) represents outflow from the Carlsbad Irrigation District and inflow to Red Bluff Reservoir. The Near Orla, TX, gage (08412500) represents outflow from Red Bluff Reservoir. The Near Girvin, TX, gage (08446500) represents outflow from combined irrigation districts of Texas, and is downstream from all substantial development for irrigated agriculture. Potentially contributing watershed area (km$^2$) is given for each station.

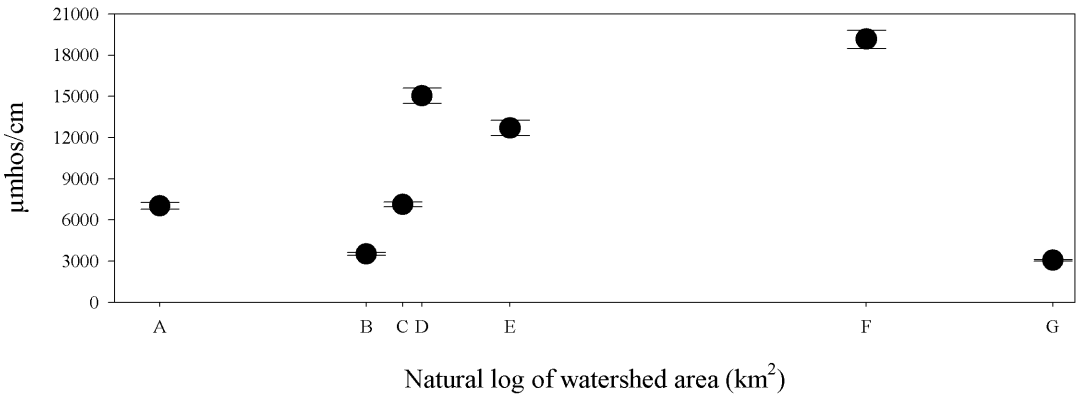


Figure 4. Mean specific conductance (μmhos/cm) at 25°C with 95% confidence intervals for the period of record at selected U.S. Geological Survey gaging stations: gage A = Near Artesia, NM, immediately upstream of the Lower Pecos River (*n* = 1,144), gage B = Below Dark Canyon in Carlsbad, NM, near the springfed headwaters of the Lower Pecos River (*n* = 226), gage C = Near Malaga, NM, at the downstream end of the Carlsbad Irrigation District (*n* = 889), gage D = Red Bluff, NM, immediately upstream of Red Bluff Reservoir (*n* = 794), gage E = Near Orla, TX, immediately downstream from Red Bluff Dam (*n* = 280), gage F = Near Girvin, TX, at the downstream end of irrigation developments along the Pecos River (*n* = 240), and gage G = Near Langtry, TX (*n* = 1,826) near the confluence of the Pecos River with the Rio Grande. The period of record for all gages was between 1959 and 2007.

short section between McMillan and Avalon dams, where streamflow infiltrated the limestone outcrop that forms the boundary between the Roswell and Permian basins (USNRPB 1942; Mourant and Shomaker 1970; Shomaker 1971). Even in this case, local losses from the river channel were more than replaced a short distance downstream via discharge from springs (USNRPB 1942; Cox 1967). The total sum of these streamflow sources is unknown, but it has been estimated that total groundwater discharge from the Roswell Basin alone produced 14.6 $m^3/s$ prior to 1900 (Fiedler and Nye 1933; Morgan 1938; USNRPB 1942). This is much higher than the base flow that presently enters the Lower Pecos River (Fig. 5), but it serves as a conservative estimate of predevelopment base inflow because groundwater inflows upstream from the Roswell Basin and surface-water inflows from the entire catchment are not included.

Additional gains within the Lower Pecos River further augmented streamflow. For example, Carlsbad Springs discharged 0.2 $m^3/s$, 2.3 $m^3/s$ entered the river within a 4.0 km reach downstream, and 1.4 $m^3/s$ entered the river between Red Bluff Dam and Girvin, TX (Lee 1925; Grover et al. 1922). Hence, predevelopment base flow at Girvin was at least 18.5 $m^3/s$, but developments that depleted streamflows were already underway when these estimates were made (USNRPB 1942). Thus, even though the estimated predevelopment base flow at Girvin (18.5 $m^3/s$) is an order of magnitude greater than contemporary base flow (Fig. 5), this estimate is conservative.

Predevelopment inflows to the Lower Pecos River have been virtually eliminated by aquifer depletion and diversion onto croplands (USNRPB 1942; Thomas 1959; Cox 1967). The historical Pecos River channel is dewatered downstream from Avalon Dam, but springs near Carlsbad, NM, reestablish streamflow (Cox 1967). Streamflow increases further between Carlsbad and Red Bluff Dam (Fig. 5), mostly from irrigation returns (Howard 1942b; USNRPB 1942), but these gains have diminished over time via aquifer depletion (USNRPB 1942; Davis 1987). Streamflow presently declines between Red Bluff, NM, and Girvin, TX (Fig. 5), as a result of reduced inflows and groundwater overdraft (Grozier et al. 1968; Richey et al. 1985; LaFave 1987). Seepage losses between Red Bluff Dam and Girvin sometimes exceed 50%, which can cause streamflow to cease altogether during dry periods (Grozier et al. 1966). Pecos River salinity is presently highest at Girvin (Fig. 4), where discharge is lowest (Fig. 5).

### Increased Evapotranspiration

Evaporation from reservoirs may increase salinity downstream depending on climatic conditions, water residence time, magnitude and frequency of diluting inflows, and precipitation of salts (Irelan 1971; Pionke and Workman 1974; Pillsbury 1981). For example, annual evaporation from four major Pecos River reservoirs in New Mexico (Santa Rosa, Sumner, Brantley, Avalon) varies between 49,339,560 and 61,674,450 $m^3$, depending on reservoir storage and prevailing weather (Longworth and Carron 2003). Additional evaporation occurs from the surface of Red Bluff Reservoir in Texas and other minor

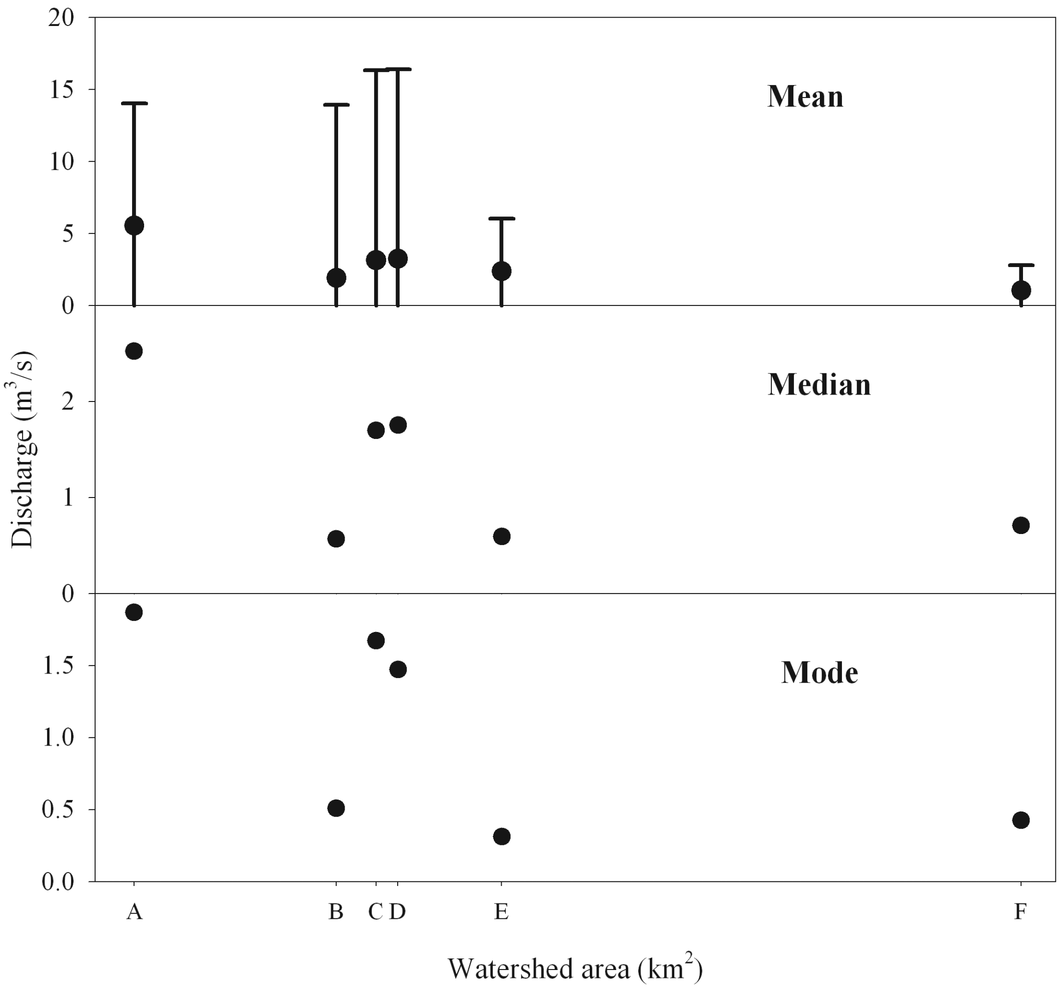


Figure 5. Average mean daily discharge for water years 1986 through 2005 from selected U.S. Geological Survey gaging stations: gage A = Near Artesia, NM; gage B = Below Dark Canyon in Carlsbad, NM; gage C = Near Malaga, NM; gage D = Red Bluff, NM; gage E = Near Orla, TX; and gage F = Near Girvin, TX. See Figure 1 for gage locations. Three measures of average discharge are presented: (1) mean discharge with standard deviation (this measure is heavily influenced by floods), (2) median discharge, and (3) mode discharge (this measure is most representative of base flows).

reservoirs throughout the drainage, suggesting that salt concentrations are increased in this manner. However, the cumulative effect of reservoir evaporation on salinity in the Pecos River drainage has not been estimated.

Historically, saline lakes and marshes were abundant along the Lower Pecos River within the Permian Basin (Dearen 1996; Brune 2002). In the absence of historical surveys, the extent of such waters is uncertain. These wetlands were important habitats for native biota, notably the euryhaline Pecos pupfish, *Cyprinodon pecosensis* (Echelle and Echelle 1992; Hoagstrom and Brooks 1999; Echelle et al. 2006), but they do not necessarily indicate the river was saline. Salts accumulate in wetlands via evapotranspiration, so by definition saline wetlands discharge very little if at all (Pillsbury 1981). Discharge occurs primarily during floods, when waters are diluted and wetlands overflow. Further, the extent of most natural evaporative wetlands varies within and among years, being less during periods of low precipitation. Only spring-fed evaporative wetlands would have relatively constant evaporation rates, and they typically have relatively low salinity because inflowing water dilutes accumulating salts. In any case, the modern extent of irrigated fields is certainly much greater than that of historical wetlands, including extensive lands on river terraces that lie above modern floodplains (USNRPB 1942). Further, application of water for irrigation occurs continuously throughout the irrigation season (March through October) and year after year, being relatively independent of precipitation patterns.

In contrast to salt accumulation in natural wetlands, salt accumulation in irrigated croplands often directly affects salinity in adjacent streams via surface and subsurface irrigation return flows. Indeed, cropland drainage and wastewater discharge are critical for reducing salt buildup within irrigated soils, so salts are deliberately discharged into adjacent waterways (Pillsbury 1981; Ghassemi et al. 1995). Approximately 688 km$^2$ are irrigated within the Pecos River drainage upstream of the Permian Basin and an additional 1,319 km$^2$ are irrigated within the Permian Basin (Lingle and Linford 1961; Byrd et al. 2002). As much as 75% of the irrigation within the Pecos River drainage relies upon groundwater sources (Lingle and Linford 1961), which facilitates salinization because groundwater is naturally higher in salts than surface runoff (Allan 1995). Repeated application of irrigation-return flows to crops multiplies the effects of evapotranspiration on salinity. Return flows from these croplands increase the salinity of the receiving Pecos River (USNRPB 1942; Pillsbury 1981; El-Ashry et al. 1985). Pecos River streamflow between Carlsbad, NM, and Girvin, TX, is primarily irrigation-return flow except during floods (Howard 1942b; USNRPB 1942). The Pecos River near Girvin is downstream of all major diversions and croplands (USNRPB 1942; Lingle and Linford 1961). Streamflow in this vicinity has the highest average salinity in the study area (Fig. 5) and derives primarily from residual waters used many times over for crop irrigation.

### Increased Prevalence of Saline Groundwater

Major aquifer overdrafts have occurred throughout the Pecos River drainage (Thomas et al. 1963; Ashworth 1990). Historically, aquifers chosen for withdrawals were relatively fresh and more suitable for crop irrigation and other uses (USNRPB 1942). Overdraft of fresher aquifers depleted relatively fresh groundwater but left more saline groundwater behind (Hood 1963; Havenor 1968; Ashworth 1990). Relatively saline irrigation-return flows now recharge these aquifers, further increasing their salinity (Ashworth 1990). Under modern conditions, the majority of discharging groundwater is relatively saline either via contamination from irrigation-return flows or from lack of exploitation due to natural salinity.

The initial source of streamflow in the modern Lower Pecos River is springs downstream from Avalon Dam, NM, which discharge a mix of fresher groundwater and saltier leakage from Avalon Reservoir (USNRPB 1942). The fresher groundwater dilutes Pecos River streamflow within the city of Carlsbad, but salinity increases dramatically within a relatively short distance downstream (Fig. 4) due to the increasing dominance of irrigation-return flows (Howard 1942b; USNRPB 1942). High-salinity inflows farther downstream, near Malaga, NM, are a mix of irrigation return flow and brine aquifer discharge (USNRPB 1942). A small amount of saline inflow is also contributed by seeps and springs between Red Bluff Dam and Girvin, TX (USNRPB 1942). Nevertheless, groundwater contributes relatively little to Pecos River flows between Orla and Girvin (Grozier et al. 1966; 1968), which is a major change from predevelopment conditions (Grover et al. 1922; Brune 2002). Downstream from Girvin, groundwater inflows incrementally increase and dilute streamflow (Linam and Kleinsasser 1996; Fig. 4).

### Cumulative Causes of Salinization

Salinization is not necessarily a result of any single source or disturbance. Indeed, many human disruptions of hydrology have potential to increase evaporation or decrease salt export, both of which contribute to salinization (Pillsbury 1981). Salinization is the cumulative result of hydrological change, so relative levels of salinization indicate the level of hydrological degradation. The Pecos River is most saline near Girvin, TX, the point downstream from virtually all cumulative impacts of agricultural developments.

Brine aquifer discharge near Malaga, NM, is a major source of salt within the contemporary Lower Pecos River (Howard 1942b; Lingle and Linford 1961; Havens and Wilkins 1979). However, effects of this discharge on streamflow salinity in the Pecos River depend on the relative volume and salinity of brine versus that of the receiving Pecos River. Historical discharge from the brine aquifer near Malaga was estimated as 0.01 m$^3$/s (USNRPB 1942). Recent base flows in the Pecos River near Malaga are less than 4.00 m$^3$/s and are comprised primarily of relatively saline irrigation return flows. Thus, historical brine inflows near Malaga would compose more than 0.2% of the streamflow in the Pecos River and add salts to already-saline waters.

In contrast, historical discharge from the brine aquifer near Malaga would have constituted less than 0.006% of predevelopment streamflows, based on the conservative estimate of 17.10 m$^3$/s (combined estimated predevelopment groundwater inflows to the Lower Pecos River and gains between Carlsbad and Malaga, NM; Lee 1925; Fiedler and Nye 1933; Morgan 1938; USNRPB 1942). Further, predevelopment streamflows were derived directly from surface runoff and unexploited aquifers that were uncontaminated by irrigation-return flows. Thus, their salinity would have been lower than at present. In other words, the capacity of predevelopment Pecos River streamflow to dilute brine inflows would have been greater in addition to having a relatively high volume. Relatively frequent floods of relatively high magnitude would have further diluted streamflows and hastened salt export. Thus, although brine discharge near Malaga contributes significantly to the salt load of the Lower Pecos River at present, it would have had much less influence on streamflow salinity prior to water resource development. Perhaps enough to create a salty taste noted by explorers and pioneers, but not enough to eliminate freshwater organisms.

Although the Pecos River in the vicinity of Girvin, TX, is now the most saline location on the Pecos River and is prone to streamflow intermittence, this was far from the case prior to development. The historical character of the Pecos River near Girvin was relatively well documented, because Horsehead Crossing, a river ford of historical importance, was nearby (Dearen 1996). Predevelopment river flows in this vicinity were considered highly unpredictable because they seemed to be constantly changing and prone to frequent and rapid flood pulses, a condition that prevailed throughout the region (Dearen 1996). Early surveyors reported that water depths in the region were commonly between 1.5 and 7.6 m (Pope 1854). Thus, historical accounts and historical groundwater data agree that predevelopment flows were much greater than postdevelopment flows. These higher flows by definition would have diluted existing salts and exported them from the drainage.

Even today, spring inflows that rejuvenate the Pecos River downstream from Girvin, TX, dramatically dilute streamflows (USNRPB 1942; Davis 1980a, 1987). For example, mean discharge of 7.1 $m^3/s$ near Langtry, TX, at the mouth of the Pecos River (water years 1981 through 1985), produced salinities similar to those near Carlsbad, despite salinization in intervening river reaches (Fig. 4). Hence, fresher, predevelopment streamflows of much higher magnitude, combined with more frequent, higher magnitude floods, must have maintained freshwater conditions throughout the pristine Lower Pecos River.

### Biological Impacts of Salinization

The level of salinization in the Lower Pecos River corresponds to the level of human disturbance (Hoagstrom 2003). Correspondingly, native biodiversity has declined most dramatically in highly salinized river reaches. For example, invertebrate diversity (Davis 1980a, 1987; Howells 2003) and fish diversity (Davis 1987; Rhodes and Hubbs 1992; Linam and Kleinsasser 1996) are most severely depressed between Red Bluff Dam and Girvin. Many of the species present are more typical of coastal estuaries than inland rivers (Davis 1980a, 1987).

Saline aquatic habitats are a natural feature of the Pecos River valley. A relatively diverse assemblage of native euryhaline fishes (Echelle and Echelle 1992; Table 1) and some euryhaline molluscs (Taylor 1985) suggests such habitats have been present for millennia. However, the euryhaline fishes (e.g., gizzard shad *Dorosoma cepedianum*, plains killifish *Fundulus zebrinus*, rainwater killifish *Lucania parva*, western mosquitofish *Gambusia affinis*, and Pecos pupfish *Cyprinodon pecosensis*) are characteristic of shallow or low-velocity habitats, not swift main-channel habitats that were typical of the predevelopment Lower Pecos River. Presumably, these fishes historically inhabited saline wetlands and springs found in the Pecos River floodplain and along tributaries. Remnants of springs and saline wetlands still support large populations (Hoagstrom and Brooks 1999; Echelle et al. 2003, 2006). The main river channel of the predevelopment Pecos River likely provided some low-velocity habitats along its margins and served as an important dispersal corridor for euryhaline fishes, but as human disturbances desiccated the Pecos River, low-velocity, high-salinity habitats became increasingly prevalent and euryhaline species came to dominate the fish fauna (Campbell 1958; Hoagstrom 2003).

The total native fish fauna of the Pecos River between Red Bluff Dam and Girvin, TX, will never be fully known because virtually no fish surveys predate salinization (Hoagstrom 2003). A comparison of recent (post-1985) and historical surveys from the Lower Pecos River indicates many taxa have disappeared from each river reach (upstream from Red Bluff Dam, between Red Bluff Dam and Girvin, and downstream from Girvin) and throughout the entire study area (Table 1). Portions of the Lower Pecos River that are less salinized (upstream of Red Bluff Dam and downstream of Girvin) until recently maintained a relatively diverse native fish fauna (19 and 27 species, respectively), including many freshwater fishes with relatively low salinity tolerance (noneuryhaline). Notably, the river reach upstream of Red Bluff Dam includes areas affected directly by inflows from the brine aquifer near Malaga, NM.

A relatively diverse, remnant freshwater fish fauna also persisted in 1957-58, during early decades of salinization between Red Bluff Dam and Girvin (Campbell

TABLE 1
NATIVE FISHES OF THE LOWER PECOS RIVER BY RIVER REACH

| **Species** | **Reach 1** | **Reach 2** | **Reach 3** | **Status**[a] |
|---|---|---|---|---|
| Alligator gar *Atractosteus spatula*[b] | | | E | E |
| Spotted gar *Lepisosteus oculatus*[b] | | E | E | E |
| Longnose gar *Lepisosteus osseus*[b] | P | P | P | P |
| American eel *Anguilla rostrata*[b] | E | E | E | E |
| Gizzard shad *Dorosoma cepedianum*[b] | P | P | P | P |
| Central stoneroller *Campostoma anomalum pullum* | | | E | E |
| Red shiner *Cyprinella lutrensis lutrensis* | P | P | P | P |
| Proserpine shiner *Cyprinella proserpina* | | | P | P |
| Roundnose minnow *Dionda episcopa* | E | ? | P | D |
| Rio Grande silvery minnow *Hybognathus amarus* | E | E | | E |
| Rio Grande speckled chub *Macrhybopsis aestivalis* | E | ? | P | D |
| Texas shiner *Notropis amabilis* | E | ? | P | D |
| Tamaulipan shiner *Notropis braytoni* | E | ? | P | D |
| Ghost shiner *Notropis buchanani* | | | E | D |
| Rio Grande shiner *Notropis jemezanus* | E | E | E | E |
| Phantom shiner *Notropis orca* | | | E | E |
| Pecos bluntnose shiner *Notropis simus pecosensis* | E | | | E |
| Northern sand shiner *Notropis stramineus stramineus* | P | ? | P | P |
| Fathead minnow *Pimephales promelas* | P | ? | E | D |
| Bullhead minnow *Pimephales vigilax* | | E | P | D |
| Longnose dace *Rhinichthys cataractae cataractae* | E | | | E |
| Slender carpsucker *Carpiodes carpio elongatus* | P | E | P | D |
| Blue sucker *Cycleptus elongatus* | P | ? | P | D |
| Smallmouth buffalo *Ictiobus bubalus* | P | E | P | D |
| Gray redhorse *Moxostoma congestum* | P | E | P | D |
| Mexican tetra *Astyanax mexicanus* | P | P | P | P |
| Blue catfish *Ictalurus furcatus* | E | ? | P | D |
| Headwater catfish *Ictalurus lupus* | E | E | E | E |
| Flathead catfish *Pylodictis olivaris* | P | E | P | D |
| Plains killifish *Fundulus zebrinus*[b] | E | E | E | E |
| Rainwater killifish *Lucania parva*[b] | P | P | P | P |
| Western mosquitofish *Gambusia affinis*[b] | P | P | P | P |
| Tex-Mex gambusia *Gambusia speciosa* | | | P | P |
| Pecos pupfish *Cyprinodon pecosensis*[b] | E | E | E | E |
| Green sunfish *Lepomis cyanellus* | P | E | P | D |
| Warmouth *Lepomis gulosus* | P | E | E | D |
| Bluegill *Lepomis macrochirus macrochirus* | P | E | P | D |
| Longear *Lepomis megalotis* | P | E | P | D |
| Largemouth bass *Micropterus salmoides salmoides* | P | E | P | D |
| Rio Grande darter *Etheostoma grahami* | | | P | P |
| Greenthroat darter *Etheostoma lepidum* | E | | | E |
| Bigscale logperch *Percina macrolepida* | P | E | | D |
| Freshwater drum *Aplodinotus grunniens*[b] | | E | P | D |
| Rio Grande cichlid *Cichlasoma cyanoguttatum* | | P | P | P |
| **Total native fishes** | **33** | **26** | **39** | **44** |
| **Extirpated native fishes** | **14** | **19** | **12** | **13** |

Notes: Modified from Hoagstrom (2003); Reach 2 records from Hoagstrom (1994), Larson (1996), Linam and Kleinsasser (1996). Reaches: 1 = Brantley Dam to Red Bluff Dam, 2 = Red Bluff Dam to Girvin, TX, 3 = Girvin to Rio Grande. E = extirpated (locally extinct), P = persistent, ? = presurvey extirpation?

[a] Study area status, based on post-1985 surveys: D = declining, E = extirpated, P = persistent.

[b] Euryhaline fishes that can inhabit waters with salinities equal to or exceeding sea water (Gunter 1942; Smith and Miller 1986; Echelle et al. 1972; Hoagstrom and Brooks 1999).

1958). Prior to 1950, irrigation from groundwater in the Texas portion of the Permian Basin was relatively minor, and springs still contributed to Pecos River streamflow (Lingle and Linford, 1961; LaFave 1987; Brune 2002). Subsequent groundwater overdraft greatly reduced spring inflows and ultimately reversed the flow direction in some reaches, causing conveyance losses via seepage into the aquifer (Grozier et al. 1966, 1968; LaFave 1987). This final desiccation corresponded with the disappearance of native freshwater fishes (Hoagstrom 2003). During the same period, nonnative euryhaline fishes become established, further threatening native taxa (Minckley 1965; Hillis et al. 1980; Childs et al. 1996). These cumulative effects of human disturbance have devastated the native fish fauna (Hoagstrom 2003). Although undocumented, it is likely the same was true of the native invertebrate fauna.

The Pecos River between Red Bluff Dam and Girvin now supports primarily euryhaline fishes (Linam and Kleinsasser 1996; Table 1). Based on post-1985 surveys, only seven of 26 native fish species remain (Table 1). In addition, eight species never collected between Red Bluff Dam and Girvin were historically collected upstream and downstream (Table 1). It is unlikely that predevelopment distributions of these species would have been disjunct, given that habitat conditions were similar throughout the study area (Dearen 1996; Hoagstrom 2003; Brune 2002; Hoagstrom et al. 2008). Rather, these species were probably generally distributed under predevelopment conditions, and their absence from historical collections indicates they disappeared from this river reach during the 50 years of intensive water-resource development that preceded extensive fish surveys. If so, the predevelopment fish fauna between Red Bluff Dam and Girvin included at least 34 fish species, of which only seven (21%) are extant.

Additional environmental degradation associated with severe human disturbances in the Lower Pecos River includes blooms of toxic algae. These blooms devastate molluscs and fishes (James and de la Cruz 1989; Rhodes and Hubbs 1992) and facilitate establishment of nonnatives (Childs et al. 1996). Toxic algal blooms are best documented in Red Bluff Reservoir and downstream, but have recently occurred upstream of Red Bluff Reservoir as well and may contribute to the recent or near-future disappearance of native fishes (Zymonas and Propst 2007).

Similar to the Lower Pecos River, invertebrate and fish faunas of the salinized Rio Grande downstream from the New Mexico-Texas border have relatively low biodiversity and consist only of salt-tolerant forms (Hubbs et al. 1977; Davis 1980b). Also, freshwater inflows farther downstream rejuvenate the Rio Grande freshwater fauna (Hubbs et al. 1977; Davis 1980b). This reach of the Rio Grande has been subjected to the same impacts that plague the Lower Pecos River (i.e. upstream flood control, extensive irrigation, groundwater overdraft). However, salinization in the Rio Grande is not commonly attributed to a brine aquifer. Rather, upstream impoundment and repeated application of river water to crops is widely recognized as the cause (Haney and Bendixen 1953; Holmes 1971; Pillsbury 1981; Meybeck et al. 1989; Hibbs and Boghici 1999). Diminished streamflows and reduced flooding (Kelley 1986; Collier et al. 1996; Schmidt et al. 2003) likely have also facilitated salinization. Thus, streamflow salinization and loss of freshwater taxa appear to be regional phenomena associated with upstream agricultural developments.

## Salinization and Flow-Regime Restoration

Patterns of salinization and fish faunal composition in the Lower Pecos River indicate that flow-regime restoration could partially restore freshwater faunas. Based on a direct comparison of the flow regime of the Pecos River near Girvin to that near Langtry for the combined periods October 1, 1975, to September 30, 1978, and October 1, 1980, to September 30, 1985 (the only data available for the Pecos River near Langtry), mean discharge of 0.8 ± 0.02 95% confidence interval (CI) $m^3/s$ near Girvin corresponds to mean discharge of 7.2 ± 0.55 95% CI $m^3/s$ near Langtry (U.S. Geological Survey gage data). Relatively high discharge variation near Langtry indicates increased flow fluctuations (floods) as well as increased base flow. Modal flow was 0.5 $m^3/s$ near Girvin and 6.7 $m^3/s$ near Langtry. Thus, an unknown average annual discharge between 0.5 and 7.2 $m^3/s$ is apparently adequate to reduce salinization in the Lower Pecos River.

In order to maintain a salt balance and reduce or eliminate salinization in the Lower Pecos River, salt export needs to be increased or evapotranspiration needs to be decreased (Pillsbury 1981). Water conservation could partially restore streamflows and dam operating procedures could be modified to elevate streamflows or provide flushing flows (Ghassemi et al. 1995; Postel and Richter 2003). Improved irrigation efficiency can potentially reduce discharge of salts from croplands (Holmes and Talsma 1981; Ghassemi et al. 1995; Hatton and Nulsen 1999), possibly also leading to reduced evapotranspiration if less water is applied to crops. Altering patterns of reservoir storage might also reduce evaporation if residence times in Brantley and Red Bluff reservoirs were reduced. Evaporation is particularly high in these reservoirs because their vicinity is relatively warm and they have high surface-area-to-volume ratios, which increase the evaporative surface relative to upstream reservoirs (i.e., Santa Rosa and Sumner). Further, underlying strata in Brantley and Red Bluff reservoirs are relatively prone to dissolution (Lee 1925; USNRPB 1942), which could contribute additional salts to reservoir waters. More extreme options for reestablishing a salt balance in the Lower Pecos River include a reduction in irrigated acreage to reduce evapotranspiration or dam removal to restore natural flow regimes and reduce evaporation.

### Salinization of Great Plains Rivers

Given the prevalence of irrigated agriculture (Parton et al. 2003, 2007), salinization is a threat to native aquatic organisms throughout the Great Plains. Indeed, increasing streamflow salinity associated with irrigated agriculture is widespread (e.g., Colby et al. 1956; Miller et al. 1981; Dennehy et al. 1998; Shirinian-Orlando and Uchrin 2000). Climate-change models indicate water demand for agriculture will increase in response to global warming (Ojima et al. 1999; Joyce et al. 2001), suggesting the threat of salinization will increase. Given that salinity has a major effect on fish distributions in the Great Plains (Echelle et al. 1972; Ostrand and Wilde 2001; Higgins and Wilde 2005), changing salinity patterns are certain to affect them. Future studies of aquatic communities in the Great Plains should include salinity measurements for better spatial and temporal documentation of regional salinity as well as to improve detection and facilitate avoidance of salinization.

The Natural Flow Regime paradigm was proposed to facilitate river conservation and restoration (Poff et al. 1997). Thus, it is fitting that flow regime restoration can potentially reduce salinization. Proponents of the paradigm have noted the importance of freshwater inflows for reducing salinity in coastal deltas and estuaries (Postel and Richter 2003), but this function is also important inland, within river drainages (Holmes 1971; Pillsbury 1981). Prior to settlement of the Great Plains, natural flow regimes of streams in the region were important for exporting natural salts. In the future, restored flow regimes may be important for exporting natural salts along with additional salt loads derived from irrigation return flows. This would not only benefit the native aquatic biota but also improve conditions for downstream water users.

## ACKNOWLEDGMENTS

I thank the College of Science at Weber State University for support, particularly Sam Zeveloff and the Department of Zoology. I also thank Jim Brooks, Jude Smith, Bob Larson, Jr., Steve Davenport, Alice Echelle, Tony Echelle, and Jim Scudday for stimulating discussions regarding the historical Pecos River. Steve Davenport, Nik Zymonas, Alice and Tony Echelle, and two anonymous reviewers provided editorial comments and encouragement. Gregory Pierce and Heber Lefgren prepared the map (Fig. 1).

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